

## **WIRELESS ENGINE MONITORING SYSTEM**

### **Related Application**

[0001] This application is based upon prior filed copending provisional application Serial No. 60/489,368 filed July 23, 2003.

### **Field of the Invention**

[0002] The present invention relates to a system and method for monitoring aircraft engines, and more particularly, this invention relates to a system and method for determining an aircraft engine's current performance and downloading data for each engine of an aircraft and processing the engine data for engine maintenance and other analysis.

### **Background of the Invention**

[0003] The Federal Aviation Administration and other international aviation regulatory agencies require commercial airlines to monitor the health and status of aircraft engines. Any health and status information is

used to determine the current performance for an aircraft engine and determine if maintenance is required. Prior art techniques have been limited because of data latency and the limited amount of collected data restricted analysis. Typically, gross indicators were measured using prior art monitoring systems. Any resultant maintenance actions were reactive. For example, some prior art systems took a "snapshot" of only basic engine parameters, for example, when the aircraft had lifted to 1,000 feet after initial take-off. This data was limited to one time slot during flight and was not real time. This data never gave analysts a complete picture of an engine performance during flight. As a result, advanced prognostics and diagnostic techniques have not been used by prior art engine analysis systems.

**[0004]** Many jet engine original equipment manufacturers (OEMs), jet engine service providers that are contractually bound under engine maintenance cost per hour (MCPH) agreements, airline transport companies and military and commercial aviation companies have desired a system and method to monitor performance of an aircraft engine in real time and archive that data. Up to now, prior art systems were limited in their analysis to the prior art data "snapshots" and did not go beyond gross indicators and reactive maintenance techniques. In some prior art techniques, airlines have complied with regulatory requirements using several different monitoring systems. In one monitoring system, limited engine parameters (e.g., N1, N2, EGT and W<sub>f</sub>) have been logged by pilots in aircraft log books. As noted before, automated engine data also was recorded at take-off/cruise at 1,000 feet as a "snapshot" that is recorded

either "on board" or downloaded via ACARS using a VHF communication data link. This engine data resulted in a limited engine analysis because only one "snapshot" of the engine performance had been used and the "snapshot" never gave a true indication of engine performance during flight of the aircraft.

**[0005]** Harris Corporation of Melbourne, Florida has designed a system and method of recording performance of an aircraft engine using a ground data link unit that interfaces with numerous components of the aircraft, including the DFDAU, the aircraft digital flight data recorder DFDR, and the data multiplexing system commonly referred to as the Full Authority Digital Engine Control (FADEC) for larger jet turbine engines or Engine Control Unit (ECU) as sometimes referred with smaller jet turbine engines used on smaller aircraft, including turboprops or other engines generating less than 15,000 pounds of thrust. Hereinafter, the term "FADEC/ECU" will be used corresponding to either the term "FADEC" or "ECU" as used by the industry.

**[0006]** An example of the Harris Corporation ground data link unit is disclosed in commonly assigned U.S. Patent No. 6,047,165, and an engine monitoring system using the ground data link unit is disclosed in U.S. Patent Nos. 6,148,179 and 6,353,734, the disclosures which are hereby incorporated by reference in their entirety.

**[0007]** In the incorporated by reference '179 and '734 patents, the system and method as disclosed can provide a record of the performance of an aircraft engine by collecting engine data during engine operation, for example, in the ground data link unit, and downloading

the collected engine data over a wideband spread spectrum communications signal to a ground based spread spectrum receiver. The signal is demodulated within a ground based spread spectrum receiver to obtain the engine data for further processing. It is also possible to upload data to the ground data link unit, such as algorithms, flight management files, video and entertainment files and other data files. Although the ground data link unit as disclosed in these incorporated by reference patents is a major improvement over prior art solutions for engine monitoring, the disclosed ground data link unit is typically a large unit and interfaces with many airborne systems as described before. It would be advantageous to monitor engines in real time without resorting to the larger ground data link unit that interfaces with many systems, or by a smaller unit when the disclosed ground data link unit is not available.

#### **Summary of the Invention**

[0008] In accordance with the present invention the wireless engine monitoring system (WEMS) of the present invention overcomes the disadvantages of the prior art described above and is an engine mounted engine monitoring module mounted directly on the aircraft engine. It is not installed in an avionics department or similar fuselage location, such as the preferred location for a ground data link unit connected to many airborne units as disclosed in the incorporated by reference '179 and '734 patents. The WEMS module is interfaced to the Full Authority Digital Engine Controller (FADEC)/Engine Control Unit (EDU) on the engine. The WEMS is a small module of about 2x2x4 inches and can record, store,

encrypt and transmit "full flight" engine data. It interfaces directly to the FADEC/EDU and records hundreds of engine parameters with one second sampling frequency, as one non-limiting example. It is a miniaturized module with a preferred conformal antenna and RF transceiver to download (and upload) data using RF/802.11/cellular techniques, including any other spread spectrum techniques.

**[0009]** The "full flight" engine data allows advanced prognostics and diagnostics techniques and increases engine "time on wing" and decreases engine maintenance costs. The WEMS data could be downloaded via RF/(802.11) spread spectrum/cellular to an airport server for processing and/or transported over the internet, PSTN, cellular system or other communications network to another workstation for real-time analysis. Data can be uploaded to the wireless engine monitoring system module, including algorithms for on-board processing.

**[0010]** The system and method of the present invention is an automated wireless solution installed directly on the engine. It records full flight engine data for large and small turbine engines and has large megabyte files, using a high speed data link to extract. The system can use a wideband spread spectrum communications signal in accordance with 802.11 standards, e.g., the technology as disclosed in the incorporated by reference '165 and '734 patents.

**[0011]** In accordance with the present invention, the system and method provides a record of the performance of an aircraft engine. An engine monitoring module is mounted on the aircraft engine and collects engine data relating to operation of the aircraft engine. The engine

monitoring module includes a transmitter for transmitting the engine data over a wireless communications signal. The receiver receives the transmitted engine data.

[0012] In one aspect of the present invention, the transmitter preferably comprises a spread spectrum transmitter for transmitting the engine data over a wideband spread spectrum communications signal. A conformal antenna, such as a patch antenna, is preferably mounted on the engine monitoring module to which the wireless communications signal is transmitted. A processor is operative for receiving the engine data from the receiver and further processing of the engine data. The engine data can be transferred from the receiver to the processor using an internet, a public switched telephone network, a cellular network or other communications network.

[0013] In yet another aspect of the present invention, a FADEC/ECU is operative with the aircraft engine for collecting engine data. The engine monitoring module is electrically connected to the FADEC/ECU for collecting engine data. A data address is preferably assigned to the engine monitoring module and links the data address to an engine serial number for tracking the aircraft engine. This data address preferably comprises an internet address. The engine monitoring module could also include a receiver as part of a transceiver for uploading data for onboard processing, including various algorithms used for engine monitoring.

#### **Brief Description of the Drawings**

[0014] Other objects, features and advantages of the present invention will become apparent from the detailed

description of the invention which follows, when considered in light of the accompanying drawings in which:

**[0015]** FIG. 1 is a partial fragmentary, isometric view of a jet engine showing the FADEC/ECU and the WEMS module mounted on the engine, the WEMS module interfacing with the FADEC/ECU for downloading engine monitoring data, in accordance with the present invention.

**[0016]** FIG. 2 is a block diagram showing the aircraft engine and aircraft, and the WEMS module of the present invention interfaced with the FADEC/ECU for downloading full flight engine data files and uploading algorithms and other data.

**[0017]** FIG. 3 is a fragmentary, block diagram showing WEMS engine data that can be downloaded to an airport server and transferred by PSTN, internet or cellular infrastructure to a real-time analysis workstation or other processor.

**[0018]** FIG. 4 is a block diagram showing basic elements that can be used in the present invention.

**[0019]** FIG. 5 is a block diagram showing basic components of a WEMS module that could be used in the present invention.

**[0020]** FIG. 6 is a cross-section of an example of a jet engine that generates engine events to be collected and transmitted from the WEMS module of the present invention.

**[0021]** FIG. 7 is a chart showing various jet engine event reports at engine start that could be monitored by the WEMS module of the present invention.

**Detailed Description of the Preferred Embodiments**

**[0022]** The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout, and prime notation is used to indicate similar elements in alternative embodiments.

**[0023]** The present invention is a wireless engine monitoring system (WEMS) and can use basic components of the ground data link unit as disclosed in the incorporated by reference '165, '179 and '734 patents. The system of the present invention is reduced in function and size for a WEMS module and is mounted directly to the jet engine and preferably interfaces with the FADEC/ECU. The present invention is operative for downloading data using a wireless communications signal, preferably a wideband spread spectrum communications signal, in a similar manner to the wireless ground link-based aircraft data communications system disclosed in the above incorporated by reference '165, '179 and '734 patents. It could also download via any RF connection.

**[0024]** FIG. 1 shows a WEMS module **10** that is mounted directly on the jet engine **12** and electrically connected to the FADEC/ECU control unit **14**, which is also mounted on the jet engine. The jet engine **12** shows basic elements of the turbine **16** and other components. The jet



engine cowling **18** is shown in dashed lines and WEMS module **10** is disposed within the cowling. The WEMS module **10** of the present invention includes basic functional RF and memory components, such as disclosed in the ground data link unit of the incorporated by reference '165, '179 and '734 patents. The WEMS module can be mounted at different locations on the engine depending on the type of preferred conformal antenna and the nature of the cowling **18** used in the jet engine.

**[0025]** FIG. 2 shows a basic block diagram of a FADEC/ECU **14** that is operative as a bidirectional multiplexer for signals to and from the jet engine **12**. The signals include analog and digital signals and the FADEC/ECU **14** gives commands to the engine from the flight deck **20** of the aircraft **22**. It also transmits engine status and health signals. Many signals are processed by the FADEC/ECU **14**, which then transmits the signals over an ARINC 429 bus **24** in this non-limiting example at typically 10 kilobits per second to and from the flight deck **20**.

**[0026]** The WEMS module **10** of the present invention has a separate IP address (for each module), which is linked to the serial number of the engine. The WEMS module is mounted on the engine and interfaces with the FADEC/ECU such as through another port on the FADEC/ECU or directly into the ARINC 429 bus. The radio frequency transceiver capability is built into the WEMS module and is operative for recording, compressing and encrypting full flight data files. It typically will use a conformal antenna **30** that is formed as a small patch antenna the size of a postage stamp, for example, mounted on a casing **31** that forms a protective housing for the WEMS module **10**.

Although a conformal antenna is preferred, a separate antenna could possibly be used depending on the cowlings and engine type on which the WEMS module **10** is mounted. A separate antenna could be mounted on a separate location on the fuselage or other location for enhancing communication.

**[0027]** The WEMS module **10** can use an archival data store for recording, storing and encrypting and then later transmitting "full flight" engine data. The WEMS module **10** of the present invention can record hundreds of engine parameters with a preferred one second sampling frequency. The WEMS module thus allows advanced prognostics and diagnostic techniques to increase "time on wing" and decrease engine maintenance costs. For example, the WEMS module **10** could be operative with jet engine diagnostic cells, such as used with prognostic and health management applications, including those designed by Impact Technologies, LLC of Rochester, New York. The WEMS module **10** can download engine data by almost any type of radio frequency signal, including spread spectrum modulation techniques. The WEMS module **10** could be operative with cellular, internet, or PSTN communication infrastructures to download full flight engine data files and upload algorithms or other data or programs. Each WEMS module will typically include a separate IP address such that it can be separately addressable for identification and upload and download of data.

**[0028]** FIG. 3 shows a high level block diagram of an aircraft **22** that includes the WEMS module **10**, which downloads engine data and uploads data for onboard processing to and/or from an airport server **32**, which could be operative with a communications network **34**, such

as a public switched telephone network (PSTN), the internet or a cellular infrastructure. The airport server **32** includes a receiver and transmitter and communicates through the communications network **34** to a real-time analysis workstation or other similar processor **38** where the engine data can be analyzed to determine the best maintenance program for an engine, and thus, extend the time the engine remains on the plane without removing the engine. The real-time analysis workstation **38** could be directly connected to the airport server or could receive data directly from the WEMS module **10**, in accordance with the present invention.

**[0029]** As noted before, the WEMS module **10** can be operative similar to the ground data link unit in that it stores data and transmits the data using a preferred spread spectrum or other wireless communications signal. The WEMS module **10** is much smaller, however, and mounts directly onto the aircraft engine. It has fewer functions than the functions required by a large scale ground data link unit, which is operative with many aircraft components, including the DFDAU, DFDR and engine sensors.

**[0030]** Referring now to FIG. 4, there is shown a representative example of an overall communications system architecture for a wireless spread spectrum data communications system that can be used with the WEMS module **10** of the present invention. The architecture in this example has three interlinked subsystems: (1) an engine WEMS subsystem **100**; (2) a ground subsystem **200** (typically airport based but not necessarily at the airport); and (3) a remote engine data control center **300** used for analyzing any downloaded engine data. The WEMS

system **100** for one aircraft **22** could include a plurality of WEMS modules **10**, each installed on an engine **100a-d**. Two aircraft **22** and **22'** are illustrated each with respective WEMS modules **10**, **10'**. Each WEMS module **10**, **10'** includes an airborne unit (AU) **102**, **102'**, each which includes the processor, transceiver, memory and other necessary components. Each WEMS module **10**, **10'** is operative to communicate with a wireless router (WR) segment **201** of the ground subsystem **200** through a wireless communications link **120**. The following description proceeds with reference to one aircraft **22** and WEMS module **10** for purposes of description.

[0031] The wireless router segment **201** routes the engine data files it receives from the WEMS module **10**, either directly to an airport base station **202** via a wired Ethernet LAN **207**, or indirectly through local area networks **207** and airport-resident wireless bridge segments **203** in this one non-limiting example. The wireless communication link **120** can be a spread spectrum radio frequency (RF) link having a carrier frequency lying in an unlicensed portion of the electromagnetic spectrum, such as within the 2.4-2.5 GHz S-band as one non-limiting example. The wireless communication link **120** could also be an RF, internet, cellular, or other link.

[0032] The ground subsystem **200** in this example includes a plurality of ground and/or airport-resident wireless router segments **201**, one or more of which are distributed within the environments of the various airports served by the system. A respective ground and/or airport wireless router **201** is operative to receive engine data that is wirelessly down-linked from a

WEMS module **10**. Each ground subsystem wireless router **201** can forward engine data to a server/archive computer terminal **204** of a base station **202**, which can reside on a local area network **207** of the ground subsystem **200** at an airport or other location.

[0033] The base station **202** can be coupled via a local communications path **207**, to which a remote gateway (RG) segment **206** is interfaced over a communications path **230**, to a central gateway (CG) segment **306** of a remote engine data control center **300**, where engine data files from various aircraft are analyzed. As a non-limiting example, the communications path **230** can include an ISDN telephone company (Telco) land line, and the gateway segments can include standard LAN interfaces. Other communications networks, such as cellular, internet, or other wireless communications can be used. It should be observed that other communications media, such as a satellite links or cellular, for example, may be employed for ground subsystem-to-control center communications without departing from the scope of the invention.

[0034] The remote engine data control center **300** could include a system controller (SC) segment **301** and a plurality of workstations (WS) **303**, which are interlinked to the systems controller **301** via a local area network **305**. Engine safety, mainenance, and monitoring analysts are at the remote engine data control center **300** to evaluate the engine data files conveyed to the remote engine data control center **300** from the airport base station segments **202** of the ground subsystem **200**. The respective workstations **303** may be allocated for different purposes.

[0035] The system controller **301** can have a server/archive terminal unit **304** that preferably includes database management software for providing for efficient transfer and analysis of engine data files, as it retrieves downloaded files from the ground subsystem. As a non-limiting example, such database management software may delete existing files from a base station segment's memory once the files have been retrieved.

[0036] As described briefly above, and as diagrammatically illustrated in FIG. 5, each WEMS module **10** can include a bidirectional wireless (radio frequency carrier-based) subsystem containing a processing unit such as a microprocessor **132** and associated memory or data store **134**, serving as both an archival data store **134a** and a buffer **134b** for communications, including packet communications. The memory **134** is coupled to the FADEC/ECU. Processing unit **132** can receive and compress the engine data and store the compressed data in its associated memory **134**. A report can be generated by the processing unit **132**, which includes many items of engine data.

[0037] The engine data and reports can be downloaded via the RF transceiver **136** and its preferred conformal antenna **30**. To provide bidirectional RF communication capability, the transceiver **136** is operative with the wireless router **201** for upload and download of data.

[0038] If the RF communication link is spread spectrum, and a preferred 802.11 link, each of a plurality of sub-band channels of an unlicensed 2.4-2.5 GHz S-band segment of interest in this non-limiting example can be available and preferably used. Other unlicensed or licensed bands could be used. A wireless

router **201** could continuously broadcast an interrogation beacon that contains information representative of the emitted power level restrictions at an airport. Using an adaptive power unit within its transceiver, the WEMS module **10** could respond to this beacon signal by adjusting its emitted power to a level that will not exceed communication limitations imposed by the jurisdiction governing the airport. The wireless (RF) transceiver **136** then accesses the engine data file stored in memory **134**, encrypts the engine data and transmits the engine data file via a selected sub-channel of the wireless ground communications link to a wireless router **201**.

[0039] The recipient wireless router **201** forwards the data file to the base station segment temporarily until the file can be automatically transmitted over the communications path **230** to the remote engine data control center **300** for analysis. Further details of the associated components are described in the above-identified and incorporated by reference patents.

[0040] In the present claimed invention, the wireless engine monitoring system (WEMS) uses similar components as in the GDL unit described in the incorporated by reference '165, '179 and '734 patents, but has reduced size and functionality for interfacing with the FADEC/ECU and mounting on the engine. The WEMS module is installed on the engine typically under the cowl and in a location to give the best antenna and transceiver functionality, but preferably adjacent or near the FADEC/ECU. It is possible to incorporate the WEMS module with the FADEC/ECU. The WEMS module records, stores, encrypts and transmits "full flight" engine data and

interfaces directly to the FADEC/ECU. It can record hundreds of engine parameters with one second sampling frequency as an example and is a miniaturized module with a conformal antenna. It acquires "full flight" engine data and allows advanced prognostics and diagnostics techniques either on-board or preferably at a remote workstation to increase "time on wing" and decrease engine maintenance costs. It is an automated wireless solution installed directly on the engine and records full flight engine data for large turbine engines and results in large megabyte files using the high speed data link as described before. It is an improvement over those systems that record only a few engine data "snapshots," resulting in limited data and limited analysis.

**[0041]** For purposes of reference, a jet engine is described with reference to FIGS. 6 and 7 on which the wireless engine monitoring system (WEMS) module **10** of the present invention can be mounted. Each engine can have one engine mounted WEMS module and each WEMS module can have a specific data address, such as an internet address or other IP address, to allow service providers to access the WEMS module and its data in near real time and perform "smart" maintenance. This address is linked to the engine serial number and will be used to store routine and critical engine information. The present invention can thus reduce engine maintenance cost per hour (MCPH).

**[0042]** FIG. 6 illustrates one cross-section of a jet engine indicated generally at **400**, showing basic components and engine air flow FADEC/ECU control **402** to and from the jet engine that can be used for real time



monitoring of engine events. These events could be downloaded during the first minute or so of initial take-off to a remote engine data control center **300** or saved to memory in the WEMS module and later downloaded to determine if "on wing" maintenance is warranted at the destination.

**[0043]** For purposes of clarity, reference numerals to describe this jet engine begin in the 400 series. As shown in FIG. 6, the engine air flow FADEC/ECU control **402** could include the core compartment bleeding; sump pressurization; sump venting; active clearance control; low pressure and high pressure recoup; and venting and draining functions. These functions could be monitored through basic FADEC/ECU control system **402**, as known to those skilled in the art. The engine example in FIG. 6 corresponds to a General Electric CF6-80C2 advanced design with a FADEC/ECU or PMC control having an N1 thrust management and common turbo machinery. Although this jet engine is illustrated, naturally other control systems for different jet engines could be used, as known to those skilled in the art.

**[0044]** The engine as illustrated has six variable stages and a ruggedized stage one blade with a low emission combustor and 30 pressurized nozzles and improved emissions. It has a Kevlar containment to give a lower containment weight and a composite fan OGV. It has an enhanced HPT with a DS stage of one blade material and a TBC, with advanced cooling and active clearance control.

**[0045]** The fan module includes an aluminum/Kevlar containment **404** and a 93-inch improved aero/blade **406**. It has composite OGV's **408** with an aluminum/composite

aft fan case **410** and a titanium fan frame **412** for reduced losses. It additionally has a four stage orthogonal booster **414** and a variable bypass valve (VBV) between the fan struts (with 12 locations) **416**. The engine includes a compressor inlet temperature (CIT) probe **418**.

[0046] The high pressure compressor includes an IGV shroud seal **420** and a blade dovetail sealing **422** with a trenched casing of stages 3-14 **424**. The compressor includes a vane platform sealing **426** and a short cord stage 8 low loss bleed system **428** and improved rubcoat reduced clearances **430**.

[0047] The compressor rear frame includes a combustor **430** and ignitor plug **432** with a fuel nozzle **434** and OGV **436**. It includes a vent seal **438** and 4R/A/O seal **440** and 4R bearing **442** and 4B bearing **444**. It also includes a 5R bearing **446** and 5R/A/O seal **448**, a diffuser **450** and pressure balance seal **452**. The compressor rear frame also includes a stage 1 nozzle **454**.

[0048] The high pressure turbine area includes an active clearance for control stages 1 and 2, and coated shrouds indicated at **456**. It also includes directionally solidified stage 1 blades and damped blades **458** and a cooling air delivery system. The high pressure turbine include a thermally matched support structure, and an active clearance control and simplified impingement with a cradled vane support and linear ceiling. The improved inner structure load path has improved roundness control, solid shrouds and improved ceiling. These components are located in the area generally at **460** of the high pressure turbine area.

[0049] Low pressure turbine technology area includes a clearance control **462**, a 360° case **464**, aerodynamic struts

**466** that remove swirl from the exit gas and a turbine rear frame **468** formed as a one piece casting.

**[0050]** Many of these components can have sensors and structural force sensor that generate signals during initial take-off such that signals are relayed via the WEMS module to an on-ground maintenance crew and/or separate remote engine data control center having its own processor.

**[0051]** FIG. 7 illustrates components that were monitored during engine start in one example, including the engine hydraulic system, the oil pressure (psi), the engine cut-off switch, oil temperature (deg C), fuel flow (lb/hr), the N2L and N1L both in percentage terms, oil temperature and EGT, both in centigrade, and  $W_f$ . Some of the ranges are shown on the vertical axis of the graph, while time is shown on the horizontal axis of the graph.

**[0052]** This information can be downloaded via the WEMS module of the present invention to a ground based processor and a remote engine data control center can determine if on wing maintenance is warranted at the destination station.

**[0053]** Many modifications and other embodiments of the invention will come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is understood that the invention is not to be limited to the specific embodiments disclosed, and that modifications and embodiments are intended to be included within the scope of the appended claims.